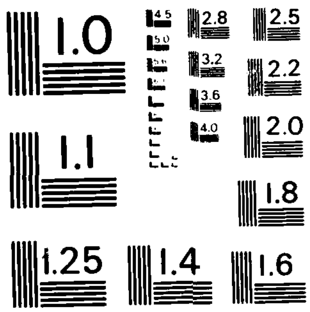

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AGARD REPORT No. 696

Some Considerations on Short Crack Growth Behaviour in Aircraft Structures

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AGARD Report No. 696

SOME CONSIDERATIONS ON SHORT CRACK GROWTH BEHAVIOUR IN AIRCRAFT STRUCTURES

This Report was sponsored by the Structures and Materials Panel of AGARD.

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PREFACE

The fracture mechanics approach for the evaluation of the safe and durable operational limits of older in-service aircraft and the fatigue life assessment of new damage tolerant aircraft structures is based upon a reliable prediction of crack growth. The new specifications for fatigue strength and durability of aircraft structures require that initial flaws of specified shape and length will not propagate to a critical crack length within a specified life time. The validity of conventional crack propagation prediction methods for crack sizes in the range of 1/10 to 1 mm (0.004" to 0.04"), however, seems to be in question since some experimental investigations have shown that small cracks obviously have a more severe effect on the crack propagation life than predicted from fracture mechanics data obtained with long crack specimens. An underestimate of the growth of initial flaws could therefore seriously overestimate the actual fatigue life.

At its Spring 1980 meeting in Athens, Greece, the AGARD Structures and Materials Panel (SMP) formed an ad-hoc group to study the behaviour of short cracks in airframe components. Following discussions at the subsequent 51st meeting in Fall 1980 in Aix-en-Provence, France, it was decided to invite the presentation of two specialist Pilot Papers which would review the state of the art of crack growth prediction techniques giving a guidance to the group for defining the task to be undertaken and for specifying the main aspects which should be covered in a future Specialists' Meeting.

The Pilot Papers from Mr Wood et al (US) and Mr Anstee and Mr Edwards (UK), which were presented at the 52nd meeting in Spring 1981 by Mr Potter and Mr Moon respectively, were judged to be of such great interest that they warrant wide distribution and therefore should be published as an AGARD document.

The paper by Mr Wood describes the uses of small crack data for the analysis of the structural operational limits of older aircraft structures, the durability design of new structures and the deterministic crack growth prediction method presently applied in the United States to determine crack growth behaviour of discrete small cracks. The paper of Mr Anstee and Mr Edwards reviews the results of a number of available experimental investigations on short crack effects and discusses surrounding effects and some additional conditions other than direct loads which obviously are influencing short crack behaviour. Both papers conclude that the analysis of small crack growth behaviour is far more complex than for the larger sizes and that the analytical prediction capability for small cracks is considerably less advanced than for the larger crack size ranges. Some of the experimental short crack data show substantial increases in crack propagation rate compared with predicted crack growth, demonstrating that further experimental work and continued research is warranted to improve the prediction of short crack behaviour.

As a result of the information and guidance the SMP agreed to form a sub-committee to develop a future Specialists' Meeting on the "Behaviour of Short Cracks in Airframe Components".

H.J. Zocher
Chairman
Sub-Committee on Behaviour of Short Cracks
in Airframe Structures

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CONTENTS

EVALUATION OF SMALL CRACKS IN AIRFRAME STRUCTURES

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Small crack technology applications to airframe structures are discussed. Cracks with the size range of 1/10mm to 1mm have been used as the starting point for evaluating the safe and durable operational limits of older in-service aircraft and as criteria for the design of new structures. The development of these criteria are presented. Evidence of service cracking obtained from teardown inspections is presented to illustrate the characteristic sizes and shapes of cracks at structural fastener holes. Current methods for predicting growth are judged to be less developed than for cracks in larger size ranges. A limited comparison of test and prediction is included. Finally, the influence of small cracks on residual strength and the potential degradation of fail safety are discussed with specific reference to a large transport aircraft. The authors conclude that the analysis of small crack growth behavior is far more complex than for intermediate and large sizes, and suggest additional research particularly the development of experimental data to support methodology development.

I BACKGROUND

This paper has been prepared to summarize small crack behavior in airframe structures. The discussion is intended to provide insight into some approaches taken to account for the development of small cracks and to utilize these developments to quantify operational limits for older aircraft, set design criteria for new structure, and help improve manufacturing processes to insure longer service lives. For purposes of this discussion, small cracks include those with sizes in the range of 1/10mm to 1mm (.004" - .04"). Because of the overwhelming importance, the discussion in this paper will be limited to fastener hole cracks. The specified range of crack sizes was chosen because of its importance to overall structural integrity. In particular:

a. The size range is characteristic of fatigue cracks at a relatively early stage of development.

b. Experience indicates that most well-designed structures can tolerate small cracks for reasonable periods of service without adversely affecting safety or performance. However, occurrences of large numbers of cracks of this size generally signal the onset of structural degradation.

c. This size range represents a level that begins to be analytically tractable by deterministic fracture mechanics methods.

d. This range is generally below detection sizes using current NDI procedures.

In summary, small cracks represent a convenient, practical, challenging and realistic starting point for structural evaluation.

In the early 1960's, the U.S. Aerospace Industry began to realize the significance of that portion of the service life of a structure which is spent in developing and growing engineering size cracks to failure. The advent of applied fracture mechanics during this period coupled with improved experimental equipment and techniques allowed for the analytical characterization and experimental verification of crack growth behavior. This discipline provided a new and valuable tool for structural evaluation. Today, the fracture mechanics discipline enjoys a prominent position within most aerospace structures departments. The philosophy that flaws exist from time of manufacture and cracks develop early in life and spend an appreciable time developing and growing is almost universally accepted. Relating "fatigue quality" or "durability" to the behavior of small initial cracks at the design stage is a technique currently receiving considerable attention in the U.S.

II SMALL CRACK DEVELOPMENT - SERVICE EVIDENCE

Until recently, very little statistical small crack data was available which represented the condition of service aircraft. The USAF has completed a series of destructive teardown inspections of high service time airframes. The articles became available because of major re-wing programs. Full-scale fatigue test articles were also reexamined in detail for evidence of small cracks. These inspections were conducted to obtain sizes, locations, and numbers of cracks to aid in establishing operational limits and optimum modification times for the remaining force aircraft. In many cases, cracking had just begun to develop and this afforded an excellent opportunity to examine the early stages of fatigue crack development. These teardowns consisted of the removal of critical areas of the structure, cleaning, disassembly and a mild acid etch to enhance visual detection. Each hole was subjected to a laboratory examination using low power optical microscopes. In one program, an entire wing of a large transport was examined including approximately 40,000 individual fastener holes. The types of cracks found are illustrated in Figure 1. The hole wall cracks and corner cracks predominated and generally were judged to be of most importance. Examples of these types of cracks are shown in Figure 2. Fatigue striations were found on samples of the findings clearly confirming the crack development mechanism. For the hole wall cracks, early development can easily be seen as the coalescence of several small origins. In only a few cases could the origin of the crack be traced to a noticeable defect in the hole. Crack shapes and sizes collected for one for these examinations are illustrated in Figure 3. The crack sizes represent the findings after several thousand service hours. Shape variability is perhaps the most obvious factor recorded. This pattern is typical of high strength aluminum, having been noted in other programs. The data shown in Figure 3 were obtained from one wing in a region with approximately the same stress level and similar stress history.

Cracking evidence of this nature can be evaluated in several ways. First the widespread and extensive nature of cracking for the wing examined can be considered indicative of a general degradation of the structure since the potential for more extensive cracking exists in one or more other force aircraft exposed to similar service usage. Similarly, the distribution of sizes can be used to statistically postulate the occurrence of larger cracks somewhere in the force. Small crack data measured at the time of teardown can be used to develop a statistical population which can then be analytically projected either forward in time to determine the critical limits or backward to time zero, the time of manufacture. In either case, individual measured cracks would be characterized and grown by analysis under known stress histories. Regression to the time of manufacturing can yield a distribution of "apparent initial cracks" and a starting point upon which to base the operational limits assessment and individual status of force aircraft. Experiences with this technique have been reported by Tiffany and others. (Ref. 1) Initial crack populations have been related to manufacturing quality, particularly hole drilling techniques. (Refs. 2, 8 and 9)

Because of flaw shape variability, analytical techniques for extending and/or regressing flaw populations require that these shape factors be normalized. One simple method is to convert each crack to an equivalent type flaw (e.g., constant shape) and base all resultant sizes on this type flaw. This procedure is illustrated in Figure 4. In this example, all cracks measured at the time of teardown were analytically extended until they reached the surface of the part. They were then converted to equivalent quarter-circular cracks, based on stress intensity, and regressed as quarter-circular, constant shaped cracks. In this way, each crack could be characterized in terms of size only.

III USES OF SMALL CRACK DATA

a. Operational Limit Analysis:

Crack population data, regressed to time of manufacture, has aided in the evaluation of operational limits for older aircraft. (Ref. 1) Criteria have been developed based on an assessment of the apparent initial crack sizes. These criteria, illustrated in Figure 5, are used to establish both the safe and economic structural limits in terms of crack growth life intervals using initial selected discrete crack size values. For safety, the assumed initial crack size was chosen to represent the maximum probable initial size (e.g., the size projected to occur on the order of once in a force population of fastener holes). The resultant size range (.030" to .050") derived from statistical data appears to be consistent with observation for numerous aircraft types. The size range is not judged to be overly conservative. In managing the force, structural inspections are performed on the basis of the safety limit. Economic and functional limits on the other hand have been derived based on average initial crack sizes from the force population of holes. In this case, considerable variability has been found in the data. The selection of the range of .002" to .005" is believed to be conservative for most cases. In managing the force, modification options are examined with the assistance of the durability limit calculations.

b. Durability Design of New Structure:

Small crack technology is being used to evaluate the durability characteristics of new structures. (Refs. 2, 3, 4, and 5) Durability design requires a disciplined procedure to select materials, processes, fabrication techniques, stress levels and structural details in order to achieve the desired service life. The objective of this approach is to minimize and/or delay service cracking which could influence airframe performance and cause expensive structural maintenance/modifications. The initial indication of a successful design occurs in the full-scale cyclic test conducted as part of the full-scale engineering development phase of every system program. (Ref. 3) At the completion of the required number of simulated service hours, the article is examined (often by teardown inspection) to determine the extent of cracking. Each incident of cracking is evaluated to determine probable cause, impact on integrity and performance, and potential corrective action required. These findings are then assessed to project the economic consequences of such cracking on the operational force. The time at which the repair costs are judged to be prohibitive is called the economic (durable) life.

Generally, the overall durability is related to the extent of cracking rather than the occurrence of a few isolated cracks. This evaluation requires that the statistical population of small cracks be developed for each region of the structure. The population is then examined to determine when the test article would reach a state of disrepair if the cracking were allowed to grow. The USAF policy (Ref. 3) states that new designs must demonstrate, by test that this condition is not reached prior to the equivalent service life time of the structure. With this success criteria established for the cyclic article, it then becomes necessary to develop routine techniques to design the airframe to achieve this goal and to predict its potential for service cracking. One basic analysis approach is illustrated in Figure 6. The predicted crack population is assumed to result from an initial set of structural factors associated with the manufacturing material, fastener fit, etc.

As discussed previously, one approach used to characterize the structure at time zero is an apparent or equivalent initial flaw size (EIFS) crack population derived from a series of test of representative details. (Refs. 1, 2 and 8) This technique is the subject of continuing research within the Air Force. (Ref. 5) The initial quality concept (Figure 6) is convenient in that the initial population can be developed and grown using deterministic fracture mechanics techniques. The population can be developed for individual parameters such as hole drilling techniques (Refs. 2 and 9) or for combinations of parameters such as hole drilling techniques, fastener fit, preload, etc. A word of caution is in order, however; the initial population derived in this manner is unique to the particular set of structural conditions and is stress level dependent. Usually one structural parameter dominates the crack development pattern. For example, in Reference 2, a study of various hole drilling techniques indicated that the most prominent crack starter was axial scratches along the base of the hole. Physical evidence from this program and others suggests that cracking does not always originate at discernable manufacturing anomalies. Many origins are related to residual stresses and local stress concentrations in the built-up structure. It may be possible, however, to characterize these structural features in terms of equivalent initial flaw populations. Therefore, it appears that a worthwhile effort would be to develop this technique into a routine design procedure.

c. Deterministic Crack Growth Prediction Methods:

The accepted method of predicting crack growth behavior of discrete small cracks is the fracture mechanics approach. (Ref. 10) The crack driving parameter is the stress intensity factor which is a function of the crack size, geometry and applied stress. The assumption of linear elasticity is usually made. The material factor used in this method is the basic growth rate, da/dn, which has been shown to be related to the stress intensity factor range ΔK. While it is generally accepted that the linear elastic approach can be used for larger crack sizes (i.e., a >1mm), some skepticism exists as to whether or not the approach is valid for small crack sizes. Very little experimental data has been published upon which to validate the fracture mechanics approach for small crack sizes. A limited amount of data was included in the study by Hsu, et al. (Ref. 7) In this study, stress intensity solutions were developed and predictions made for both constant amplitude and spectrum loading for through and part-through cracks. Comparisons of predicted and test lives are indicated in Table 1. The two materials tested were 2219-T851 aluminum and Ti-6al-4v titanium. Only constant amplitude data are presented in Table 1. All initial cracks were in the range a = .005" - .009".

Table 1 - Comparison of Predicted and Test Lives

2219-T851

THRU CRACK	R*	CORNER CRACK	R*
Open Hole	0.87	Open Hole	0.38
Close Tol. Fast	1.12	Open Hole	0.49
Loaded Hole	0.65	Close Tol. Fast	0.62
Open Hole	0.86	Close Tol. Fast	0.72
Close Tol. Fast	0.75	Loaded Hole	0.30
AVE =	0.85	Loaded Hole	0.47
		AVE =	0.490

$$R^* = \frac{\text{Predicted Life}}{\text{Test Life}}$$

Ti-6al-4v

CORNER CRACK

	R*
Open Hole	0.51
Open Hole	1.71
Close Tol. Fast	0.86
Loaded Hole	0.51
Loaded Hole	0.72
AVE =	0.862

*R = Predicted Life/Test Life.

These results yield some confidence in the ability to predict small crack behavior under simple loading. The reason for the difference between the capability to predict the behavior of corner cracks in titanium and aluminum is not clear from a review of the data. Lives for corner cracks were predicted using a constant quarter-circular shape. Some shape change was noted in the test data. One reason for the difference might be the sensitivity of the different materials to flaw shape change.

d. Fail Safe Evaluation of In-Service Aircraft:

Small crack technology has recently been used to evaluate the allowable cracking and service limits of a multiple load path military aircraft wing. (Ref. 11) The concern was that small but extensive service cracks could affect the single panel residual strength if the cracks were located adjacent to the single panel at time of failure. To establish basic strength allowables, cracked and uncracked coupons were statically tested to failure. Figure 7 includes the results of one of these tests. While data scatter is considerable, particularly to specimens with crack sizes one milimeter below a definite trend in strength reduction is noted. Normally the few percent reduction noted by these data would not be considered to be a problem because the ultimate load condition is rarely achieved in service. However, in most designs fail safety presumes that the remaining structure will be able to attain approximately the material ultimate stress in the elevated stress region adjacent to the failed member. This situation can occur with overall wing stresses well below ultimate as indicated in Figure 8. Small cracks can aggravate the situation in this case. For the problem studied by Circle and Wood (Ref. 11), the small crack data was used to develop the residual strength curve up to 1.3mm (.05").

IV SUMMARY

This paper has presented some practical aspects of small crack growth behavior as they influence structural solutions for airframes. Analytical prediction capability for small cracks at fastener holes is considerably less advanced than for the larger size ranges. Without appropriate experimental data to support small crack predictions, solutions may be unconservative. Within the USAF, small crack growth technology has been used to assess structural durability and has been particularly effective in evaluating production hole drilling techniques. The influence of small cracks on fail safe residual strength has also been assessed. Teardown inspections have been valuable sources of small crack statistics to assist in structural assessments. The techniques for finding and measuring early fatigue crack formation should be adopted to laboratory studies associated with crack development. Analysis of small crack growth behavior is far more complex than for the intermediate and larger sizes. Continued research is warranted, including additional experimental residual strength and crack propagation data to support methodology development.

REFERENCES

1. Analysis of USAF Aircraft Structural Durability and Damage Tolerance - AIAA Lecture and Workshop Program, April 1978.

2. Noronha, P.J., Henslee, S.P., Gordon, D.E., Wolanski, Z.R., and Yee, B.G.W., Fastener Hole Quality, AFFDL-TR-78-206, Dec 1978, Air Force Flight Dynamics Laboratory.

3. MIL-STD-1530A Military Standard, Aircraft Structural Integrity Program, Airplane Requirements, December 1975.

4. Shah, B.M., Buss, J.L., Lockheed-Georgia Company, "An Interdisciplinary Approach for Structural Life Estimates of Aircraft Components, AIAA Paper No. 80-0751, 21st SSDM Conference, Seattle, Washington, 11-14 May 1980.

5. Manning, S.D., Garver, W.R., and Kim, Y.H., "Durability Methods Development - Durability Analysis - State of the Art Assessment", AFFDL-TR-79-3118, Vol II, September 1979, Air Force Flight Dynamics Laboratory.

6. Manning, S.D., and Norton, J.M., "Deterministic and Probablistic Fracture Mechanics," 1978 ASQC Technical Conference Transaction, Chicago, Illinois, PP 245-254.

7. Hsu, T.M., McGee, W.M., and Aberson, J.A., "Extended Study of Flaw Growth at Fastener Holes," AFFDL-TR-77-83, Air Force Flight Dynamics Laboratory, April 1978.

8. Rudd, J.L., "Applications of The Equivalent Initial Quality Method," AFFDL-TM-77-58-FBE, Air Force Flight Dynamics Laboratory, July 1977.

9. Potter, J.M., "Advances in Fastener Hole Quality Through the Application of Solid Mechanics," Proceedings of the Army Symposium on Solid Mechanics, 1978, AMMRC-MS-78-3, Sept 1978.

10. Wood, H.A., Engle, R.M., Gallagher, J.P., and Potter, J.M., "Current Practice on Estimating Crack Growth Damage Accumulation with Specific Application to Structural Safety, Durability and Reliability," AFFDL-TR-75-32, Air Force Flight Dynamics Laboratory, January 1976.

11. Circle, R.L., Lockheed-Georgia Company and Wood, H.A., Aeronautical Systems Division (USAF), "Fail Safety Limitation for Multiple Load Path Aircraft Structure Resulting From Service Fatigue Cracking." To be presented at the International Conference on Aeronautical Fatigue, The Netherlands, May 1981.

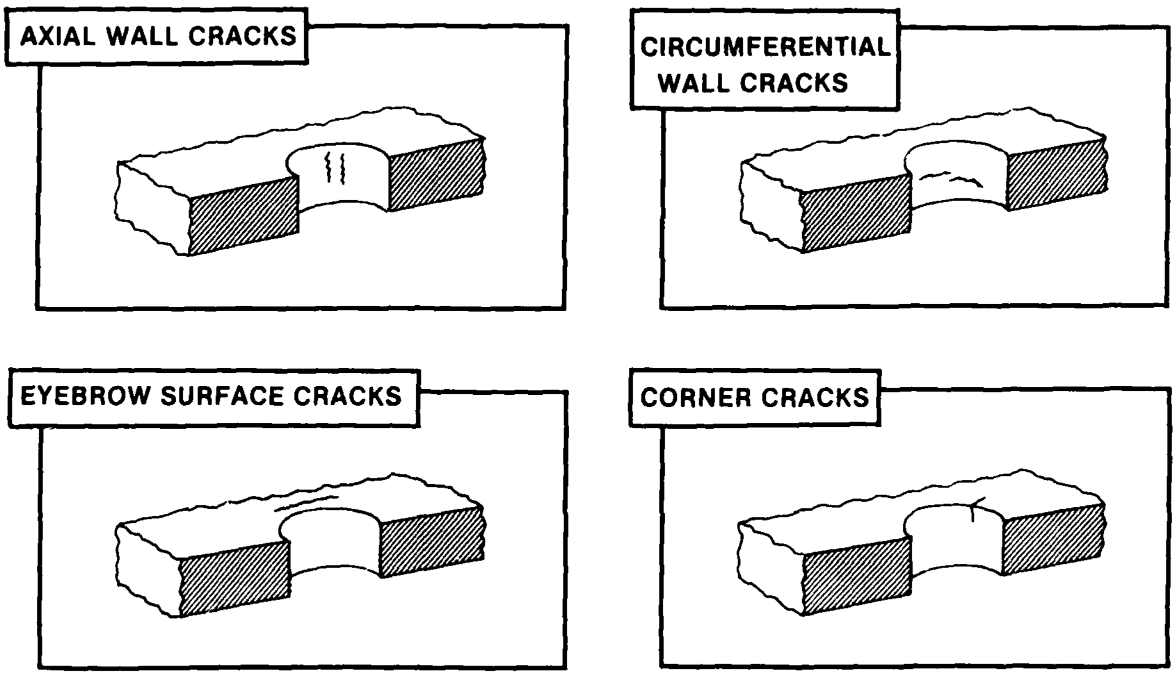


FIGURE 1 - CRACK TYPES FOUND IN TEARDOWN

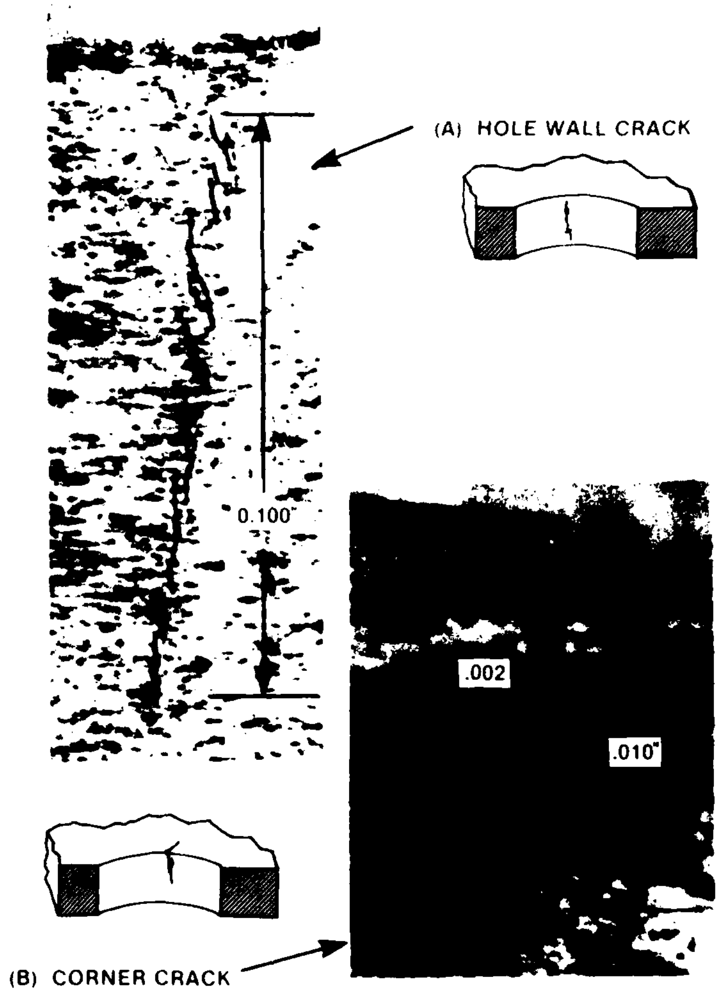
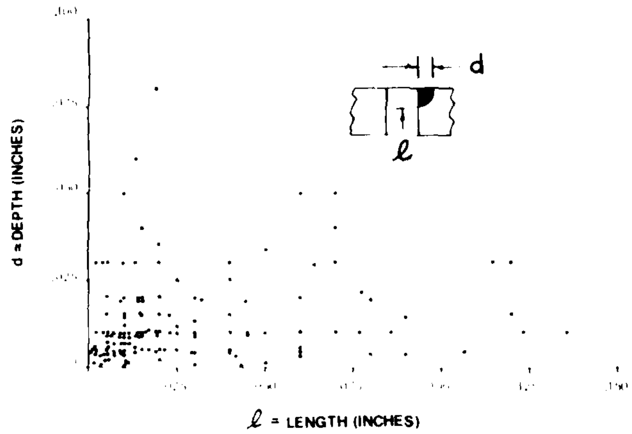
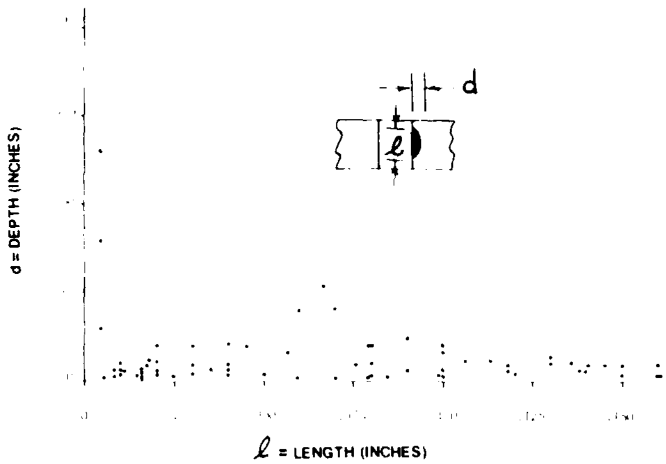


FIGURE 2 - TYPICAL SMALL NATURAL CRACKS



(a) CORNER CRACKS



(b) AXIAL HOLE WALL CRACKS

FIGURE 3 - CRACK DATA FROM TEARDOWN INSPECTION

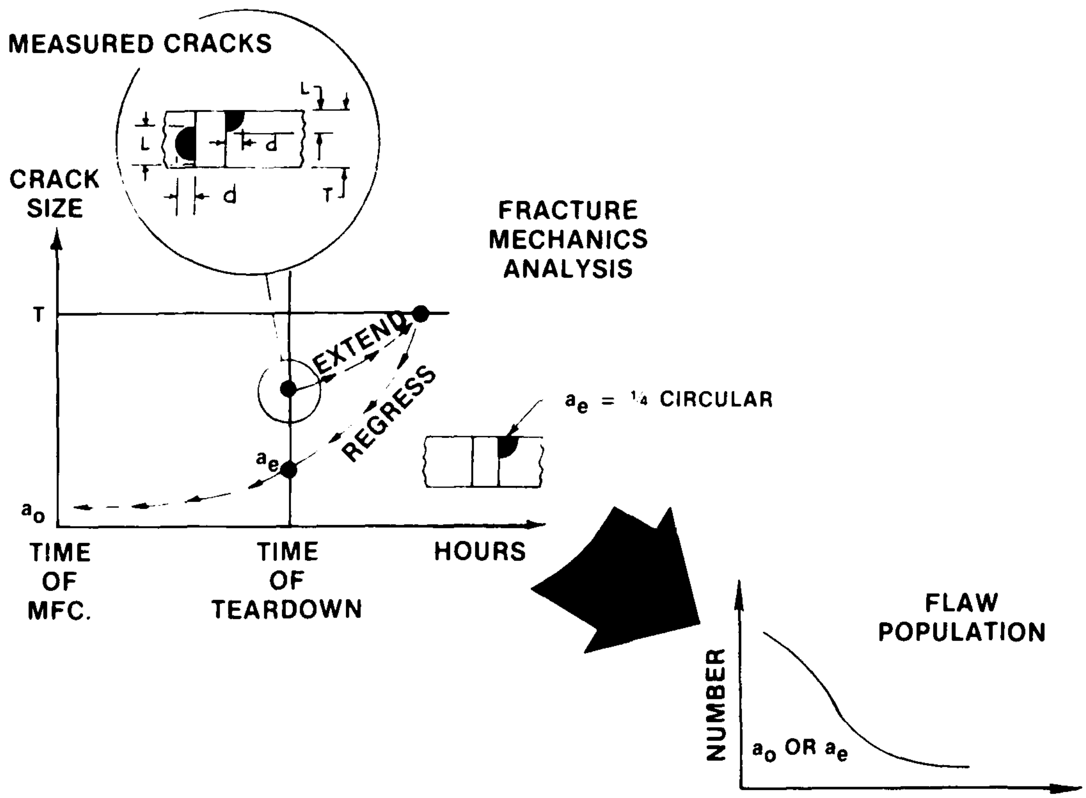


FIGURE 4 - DEVELOPMENT OF FLAW POPULATION

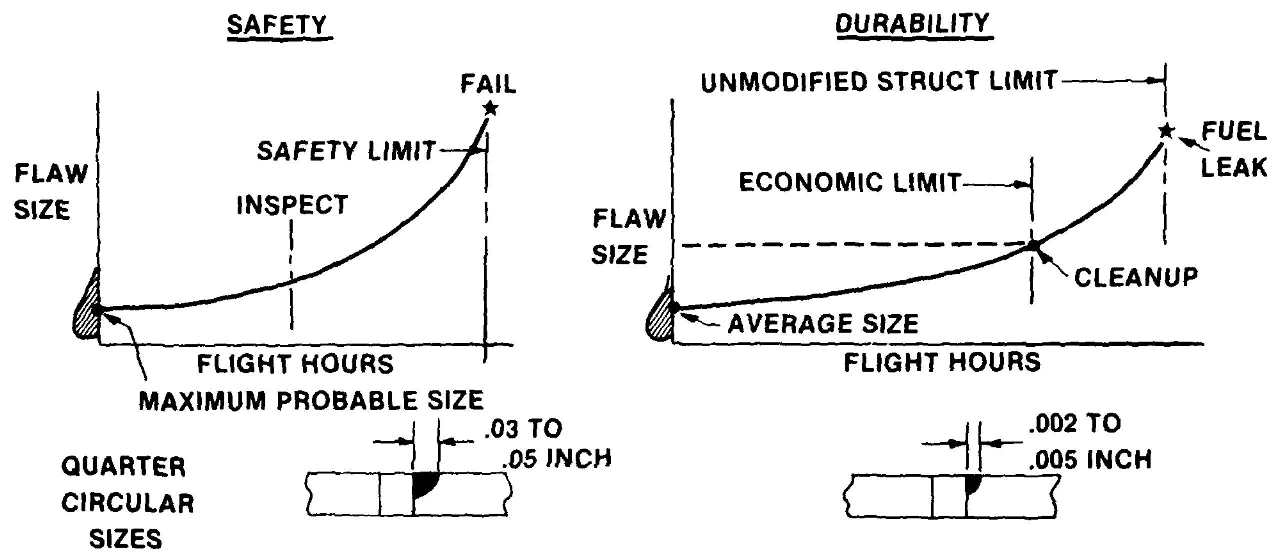


FIGURE 5 - CRITERIA FOR OPERATIONAL LIMITS ANALYSIS

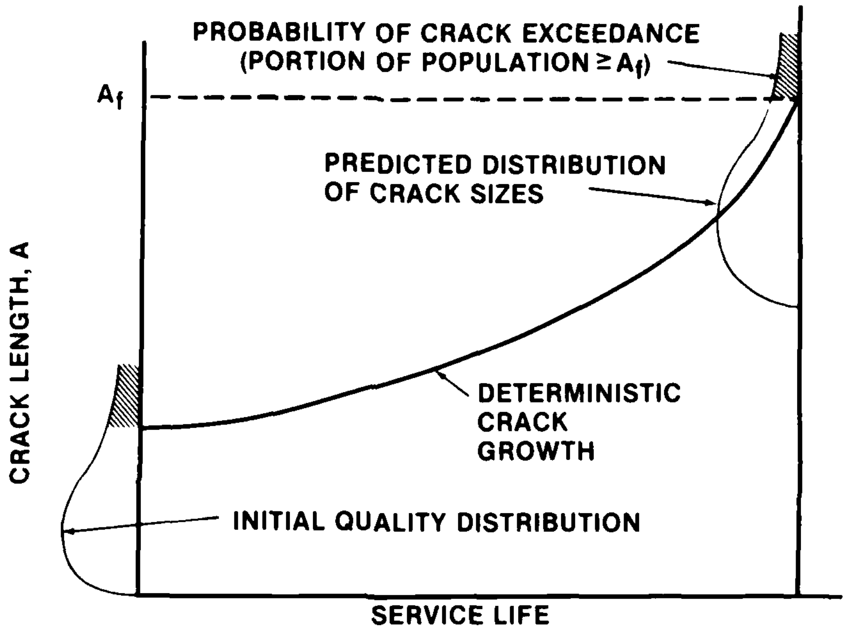
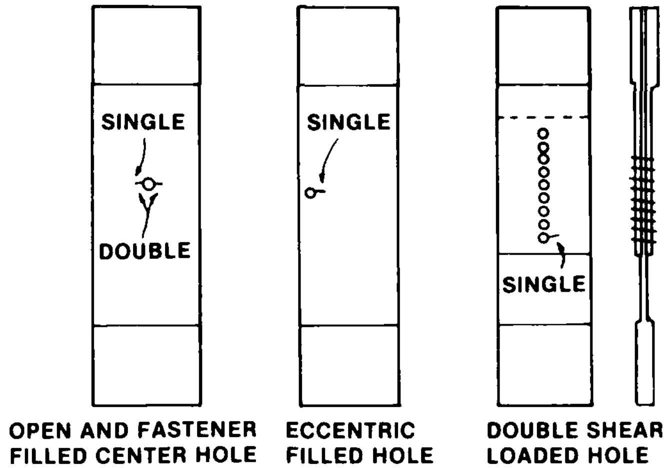
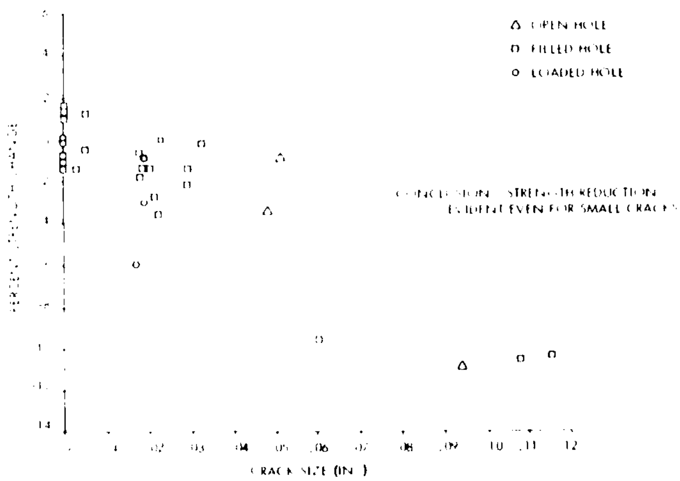


FIGURE 6 · CRACK GROWTH APPROACH FOR DURABILITY EVALUATION



(A) TEST SPECIMENS



(B) STRENGTH DATA

FIGURE 7 - EFFECT OF SMALL CRACKS ON STRENGTH (11)

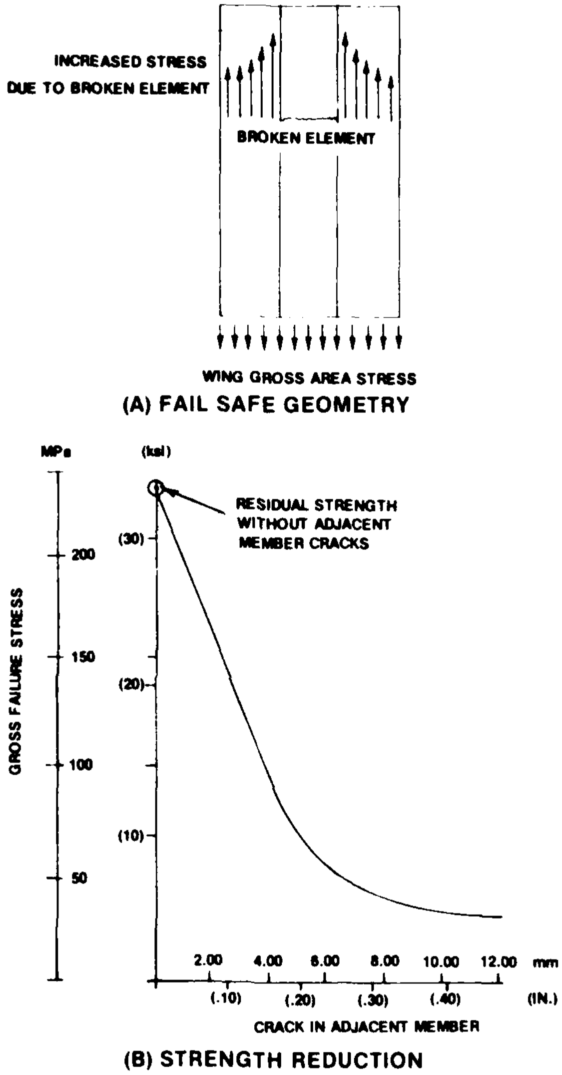


FIGURE 8 · EFFECT OF SMALL CRACKS ON ADJACENT MEMBER STRENGTH [11]

A REVIEW OF CRACK GROWTH THRESHOLD AND CRACK PROPAGATION RATES AT SHORT CRACK LENGTHS

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1 INTRODUCTION

Prior to the development of crack growth prediction techniques based upon fracture mechanics the fatigue life of a structure was determined from information on life cycles to failure related to nominal stress and stress concentration factor. Problems of durability and strength of fatigue damaged structures in service hastened the introduction of life assessment techniques based upon a prediction of crack growth. The notable example of a requirement for this approach is MIL SPEC 83444[1]. In this document an initial flaw of 0.127 mm (0.005 inch) is specified to exist at every hole, with larger flaws at the most critical locations. This does not mean however that no account is taken of fatigue crack initiation time; since the flaw specified is in practice an equivalent initial flaw which, using current crack propagation prediction techniques, gives a fatigue life which is equivalent to lives typical of service experience[2]. Support for an equivalent initial flaw size of 0.125 mm (0.005 inch) comes from the work of Forman[3] (Fig 1), who found that compared to unnotched SN data for 7075-T6 and notched SN data for 2014-T6 an equivalent initial flaw of 0.125 mm (0.005 inch) and 0.06 mm (0.0025 inch) respectively predicted the same life. Further support comes from read-back analyses of Phantom fatigue tests and the more recent results of Rice and Brock[2].

Numerous studies have been made of the effects of cracks of small size. Many have concluded that an anomaly in crack growth behaviour exists. Typically it is suggested that short crack anomalies exist for cracks less than about 0.1 mm to 0.2 mm depth. These investigations, which we shall discuss later, nearly always find a more severe effect of the crack than would be suggested from fracture mechanics data obtained with long crack specimens. There is then, concern, that since a considerable portion of crack growth life is typically obtained from the growth at small crack size, an underestimate of growth rate in this region could seriously overestimate service life. An improved understanding of short crack effects could be employed either to modify crack growth prediction techniques or to provide a more certain base for the equivalent initial flaw size.

A further reason for the understanding of short crack anomalies arises from potential material improvements. If it can be shown that such anomalies as do arise are related to metallurgical features it may be possible to eliminate these features to gain extra fatigue life, possibly in initiation as well as early propagation.

2 REASONS FOR SHORT CRACK ANOMALIES

The failure of linear elastic fracture mechanics to predict the behaviour of short cracks to the same degree of accuracy obtained for long crack behaviour must stem from one of two reasons (or possibly both). These are that either linear elastic fracture mechanics (LEFM) is not the appropriate analysis technique, or that effects not normally accounted for are important and must be included. The objective should therefore be:

i to establish the crack length at which LEFM becomes applicable,

ii to define how LEFM can be adapted or modified for use at shorter crack lengths,

iii to define what additional factors affect the growth rates of short cracks and how these factors can be characterised in the LEFM prediction techniques.

It can be seen that since the stress intensity factor K is given by:

$$K = \sigma\sqrt{\pi a} \times [\text{geometry factor}]$$

then as a becomes small with K limited to K_{TH}, the threshold value for crack growth, the stress σ will increase until it exceeds the plasticity limits set on the applicability of LEFM. One simple approach to setting a validity limit on crack length would be to assume σ equal to the plain material fatigue threshold stress and $K = K_{TH}$. Then:

$$a \text{ validity limit} = \frac{1}{\pi}\left(\frac{K_{TH}}{\sigma_{TH}}\right)^2$$

Alternative approaches could be to link crack size to material microstructure or to the extent of plasticity at the crack tip.

Factors which can often be neglected in LEFM analysis but which are likely to be important in short crack conditions fall into three categories (i) surface conditions (ii) plasticity (iii) "three dimensional considerations" in K determination. Surface conditions which reduce in importance as the crack grows are, for example, residual stresses due to machining, cold working or chemical finishing, and applied stresses due to fretting. Plasticity effects arise from the stresses in the zone of yielded material at the crack tip and also from crack closure due to the wake of yielded material left behind the advancing crack tip. The effect of the yield zone at the crack tip will be to prop the crack open[4], effectively increasing the stress cycle, while crack closure, since it occurs at positive stress levels, reduces the load cycle[5] (Fig 2). The size of crack tip yield zone relative to crack length will be proportionally much larger for small cracks than for long cracks, hence the yield zone will be more important. Conversely the crack closure mechanism cannot be established before the crack has grown and hence closure effects will be small at short crack lengths. It might also be expected that the plastic zone and crack closure effects would be affected by the ratio of minimum to maximum stress in the load cycle and whether the loading was constant amplitude or variable amplitude.

Small cracks are by definition three dimensional cracks, they do not penetrate the thickness with a near straight crack front. The K solutions for such crack shapes are fewer and less well proven than for two dimensional long cracks. There is substantial variation in K along the crack front of a corner crack[6] but negligible variation (for most purposes) along the front of idealised long cracks. The controlling K value for crack growth (or fracture) has yet to be defined, whether it be a peak K value or some summating function. However it must be probable that a crack with substantial K change along the crack front will not react in the same way as a crack with little change in K value. In final fracture terms there is some evidence that rate of change of K has a substantial effect[7]. The proportion of plane stress to plane strain material will probably be different for short and long cracks in most cases. Valid comparisons between long and short crack data should take all these factors into account.

3 REVIEW OF RESULTS FROM EXPERIMENTS

This section reviews the results which have come to the authors' attention. Other work most probably has been published and since there is considerable interest in the topic it is anticipated that this review will quickly be outdated. Results to date are in conflict in some respects, particularly since some investigations have failed to show short crack effects.

The first part of this section concentrates upon studies where surface effects are not expected to be important, these effects being considered later. The work covered starts with the early papers indicating fast growth at short crack lengths and reasons for believing that fundamental limitations on applicability of LEFM below a certain crack length should exist. It then goes on to look at the relationship of fatigue threshold stress and stress intensity factor threshold values to the short crack length. Finally the effects of microstructure and modes of crack origin are covered.

3.1 Engineering Studies

3.1.1 Crack Growth

De Lange[8] published some of the earliest work in which fast growth of short cracks could be identified. He tested six specimens of 26 ST aluminium alloy in rotating bending and six specimens of 35 CD steel in tension-compression. He recorded surface crack lengths using plastic replicas which he measured down to 2 μm (0.0001"). His results showed considerable variability. For each material three specimens showed fast initial crack growth rates, although he also found some non propagating cracks. The cracks which did grow were consistent with long crack data by a length of around 20 μm (0.001").

Pearson[9] reported tests on unnotched L65 and DTD 5050 under reversed bending at a range of R values (Fig 3). He reported very fast crack growth rates at initial lengths of 0.03 to 0.04 mm (0.0012" to 0.0016") which tended towards the rates predicted from long crack data at lengths of about 0.127 mm (0.005"). Pearsons work is a standard reference in short crack investigations. It is therefore surprising that comment has not been made on the stress levels employed. His seven L65 specimens were tested at maximum tensile stress levels of between 0.8 and 1.04 the 0.1% proof stress, which invalidates the use of LEFM. He used four DTD 5050 specimens at loads which gave maximum stresses of 0.68, 0.74, 0.78 and 1.04 the 0.1% proof. Of these the crack in the specimen tested at 0.68 proof were detected at 0.092 mm (0.0036") and presumably had little effect upon the early fast part of the curve. Subsequent examination showed considerable damage throughout the surface grains of these specimens[10]. Since the cracks all started from inclusions it is also possible that there was a local stress concentration in the parent material which should be taken into account. It can be concluded that while Pearsons results show very real effects they are a priori outside the bounds of LEFM analysis.

Work by Schijve[11] has been quoted as showing short crack effects, although significantly Schijve[12] does not refer to it himself in the context of fast growth. His work was on small corner cracks 0.2 mm (0.008") which grew at an apparently slower rate than long crack data would suggest, from which Schijve deduced a corner crack 'K correction' (Fig 4).

Brock[13] has also been referenced elsewhere as showing fast initial growth rates. His results show considerable scatter in initial crack growth rate from the edge of a hole (Fig 5). However his results relate to growth from saw cuts at the edge of the hole. Long cracks which have been extended by a saw cut and then retested also show this same effect, due to a change in the residual stresses at the crack tip and a lack of crack closure[14,15]. It is also of significance that Brock tested clad material and observed surface cracks. It might be expected that the cladding would react in quite a different way to that of the parent material.

In discussion of short crack effects Taby[16] showed a 20% increase in crack growth rate at short crack length compared to long crack data (Fig 6). However at K values near threshold the exponent in the Paris equation will be high, probably considerably above 5. Even so, at n = 5 only a 3.5% error in K determination accounts for this difference, perhaps within the bounds of the solution used.

Tests on mild steel in both axial loading and bending under both constant amplitude and random amplitude load cycles have been reported by Fisher and Sherratt[17]. Their experiments were on cracks from depths of around 0.1 mm (0.004") at notches. The stress gradient due to the notch was calculated and included in the stress intensity range calculation. Their results while showing no very marked trends did suggest faster crack growth at short crack lengths. The tendency was more readily seen under axial loading at positive mean stress under both constant amplitude and random amplitude loading. Results under bending loads were less clear.

El Haddad[18] et al reported tests on G40.11 steel. They showed short crack effects at crack lengths up to 1 mm (0.040") and crack growth rates between 2 and 10 times faster than would otherwise be predicted. Their results were more severe than reported elsewhere. However they also reported crack growth threshold tests on specimens which were remachined to reduce the crack length after developing a sharp fatigue crack. This testing technique must be considered doubtful since plasticity effects at the crack tip and along the crack faces will be appropriate to a ΔK condition other than that applied on reloading and also the bow of the crack front relative to the crack length will be changed. This will be discussed later but it is not clear whether El Haddad's crack growth specimens were produced in this same way. In the same paper the authors re-analysed data previously reported by Dowling[19]. He tested A533B steel in completely reversed constant amplitude loading into plastic strain levels. He found for short cracks (ie $\leq$ 0.007") that the crack growth rate when plotted against ΔJ to allow for plasticity exceeded the long crack growth rate by a factor of around 2, approaching 3 at high plasticity levels.

Barnby and Holder[20] studied six steels fatigue tested in bending. It was shown that they all exhibited rapid initial propagation up to a crack length of around 0.5 mm (0.020"). (Fig 7A).

Finally Cook et al[21] studied short cracks in notched aluminium alloy specimens under constant and variable amplitude loading. Measurements were made down to lengths of approximately 0.02 mm. Under constant amplitude loading there was considerable scatter, and fast crack propagation at short crack lengths was not identified clearly. However where the threshold would have been expected the curve of da/dn v ΔK was still relatively shallow (index < 3). Fast crack propagation was found at short crack lengths under variable amplitude loading as described in Section 4.3.

A number of studies has been published by Lankford. He tested smooth waisted 4340 steel specimens at R = 0.1[22]. Using fractography to measure crack growth rates he found that by taking account of debonded inclusions he could correlate crack propagation rate using LEFM techniques. This correlation held good down to the lattice spacing (Fig 7B). He also noted non propagating cracks held at the grain boundaries. Later work[23] on large cracks machined shorter has shown both fast and slow rates. By examining specimens in a scanning electron microscope (SEM) it was shown that initial rates were faster than predicted from long crack data, reducing later to below the long crack rates before merging at a longer length. Lankford suggested from this and previous work[22] that the crack front grows initially fast until interaction with grain boundaries occurs. The growth rate was reduced by this interaction and slowly recovered to the long crack rate at a length at which the cyclic plastic zone was approximately equal to the average grain size. Recently Lankford[24] has supported this work with results from specimens cyclically loaded while under observation in the SEM. He has shown (Fig 8) a range of behaviour from very fast crack propagation similar to Pearson's results through to non propagating cracks.

Starkey and Iroine[25,26] in crack propagation studies of smooth specimens of spheroidal graphite cast iron found that they could correlate crack growth rates using the J integral approach (as ΔJ) to extend LEFM to elastic-plastic fracture mechanics (EPFM). They were able to work down to the micropore size of the material 150 µm (0.006"). Starkey[27] recently reported further work using this approach on unnotched cylinders of EN 16 steel. For this material, which has a fine grained regular structure, cracks were observed starting on the surface at about 10 µm. Measurements were recorded from lengths of about 25 µm, after 25-50% of the life had been expended. Again the EPFM approach was used to successfully correlate the test data with long crack data from 25 µm onwards.

Work by Powell[28,29] using aluminium alloy to study short crack effects under constant amplitude loading has failed to show any differences between long crack and short crack data. His tests used block loads at two R values to distinguish striation bands which were then used to obtain crack growth rates. He did however note an interaction due to change in R value.

Peel[30,31] has also used striation counting combined with LEFM to analyse the early stages of fatigue failures. Typical initial crack lengths used were as small as 0.1 mm (0.004") with no reported difficulties in analysis at short lengths.

3.1.2 Stress Intensity Factor Threshold and the Fatigue Limit (Fatigue Threshold Stress)

The stress intensity factor threshold for crack growth can be written as:

$$\Delta K_{TH} = \Delta\sigma\sqrt{\pi a}$$

As crack length a becomes small $\Delta\sigma$ increases until it reaches the value $\Delta\sigma_{TH}$, the fatigue limit for plain specimens above which fatigue damage must occur (Fig 9). These two boundaries define a limit for non propagating cracks, the study of which has generated much of the threshold data available. Pook[32] in studies of non propagating cracks reduced the length of existing long cracks by machining and studied their subsequent re-initiation behaviour. He found a marked reduction in K_{TH}, typically down to 60% of the previous values obtained with long cracks (Fig 10).

More recently there has been considerable interest in threshold conditions and non propagating cracks, and the interaction of crack length and threshold values. Numerous investigations have shown that below a certain crack size the threshold stress is no longer ΔK dependent but reduces steadily below the $\sqrt{a}$ relationship of LEFM until the fatigue limit stress is attained (Fig 11). Much of the work has centred on defining this crack size (which may be thought of a the small crack LEFM limit), or determing an expression for the curve joining the two threshold lines, in order to extend the applicability of LEFM. To investigate this Kitagawa and Takahashi[33] used a 50 m (0.002") arc strike pit as a crack initiator. They found it was acceptable to use a crack length of 0.1 mm as an LEFM short crack limitation. Kitagawa[34] in a separate publication suggested a strain intensity factor which showed good correlation down to the smallest crack size measured for a range of bending tests at R = -1 and -0.82 and tension tests R = 0.

He proposed $$K_\varepsilon = \varepsilon\sqrt{\pi a} = \eta\,(\Delta\tau)^n\sqrt{\pi a}$$

and $$\frac{da}{dn} = C\,\eta^m\,(\Delta\tau)^{(n-1)m}\,(\Delta K)^m$$

Murakami[35] also suggested from his investigations that a short crack limit of 0.1 mm applied in LEFM and noted that holes in the specimen below this size had no effect on the fatigue limit. He suggested therefore that the fatigue limit was not the stress range at which no cracks appear but was in fact the stress range at which cracks did not propagate. Nisitani and Takao[36] also reported non propagatory cracks of this size from tests on plain fatigue low carbon steel specimens in rotary bending. They noted that the non propagatory crack size was approximately equal to the average grain size.

3.1.3 Stresses or Loads at the Surface

Fretting

Edwards and Ryman[37] have studied the effects of fretting on the development of fatigue cracks, and measured accelerated growth rates at lengths up to 1 mm. They showed that by including in the calculated stress intensity factor components due to normal (static) and frictional (alternating) contact stresses, it was possible to predict fretting fatigue results with reasonable accuracy. They found that it was desirable to enhance the stress intensity factor by a correction allowing for short crack effects. Using this correction gave the best fit of theoretical curves to experimental results at short crack lengths. They also found that the prediction was less good at higher stress levels. The smallest crack of significance was 0.02 mm (0.001") and non propagating cracks of around 0.20 mm (0.008") were found in unbroken specimens at the fatigue limit. Rapid initial crack growth was also found in the early stages of fretting fatigue by Leadbeater[38] et al who found crack growth rates an order faster with fretting than in plain specimen fatigue at the same crack lengths and direct stress levels. The accelerated crack growth was attributed, as above, to frictional forces. More recently Moon[39] has produced crack propagation results for bushed and unbushed lugs. He showed accelerated crack propagation results for bushed and unbushed lugs. He showed accelerated crack rates at lengths up to 1.0 mm. He showed also that lugs with an interference fit bush had a much longer life under constant amplitude loading, and a much reduced proportion of the life spent in crack propagation. This was attributed to reduced slip in the case of the bushed lug, leading to reduced frictional forces and consequently to longer initiation and slower early crack propagation rates.

Machining Stresses and Work Hardening

The effects of work hardening on the early propagation of short cracks have been noted by Heath-Smith and Aplin[40] and by Forsyth[41]. They showed the effects of drilling were significant in fatigue performance. It has also been shown that high surface stresses can result from grinding[42].

Cold Working

There is ample evidence[39,43,44,45] to show that fatigue crack initiation and the initial growth of fatigue cracks are suppressed by the residual stresses induced by cold working.

Chandwanich[44] has studied cold worked holes under constant amplitude loading at R = 0.1. He measured surface strains at every 0.1 mm (0.004") using a Moire system. Accurate measurements of crack opening were obtained by laser interferometric methods, from which stress intensity factors were derived. He found that he could not predict the observed crack growth satisfactorily. The reasons for error were suggested to be; variation in crack front shape relative to the theoretical model, changes in residual stress pattern with cycling and an inadequate model of the initial residual stress pattern.

Rich and Impellizzeri[45] reported that they were able to predict the growth of cracks at fastener holes which were either cold worked or fitted with interference fit fasteners. They did not measure crack growth below a crack length 0.25 mm (0.010"). Their analysis showed a good measure of agreement with prediction above this length.

Chemical Finishing

Many finishes which are applied affect fatigue properties. The effects of nitriding to various depths has been studied by Clark and Knott[46]. It was shown that increasing the depth of the hardened layer progressively caused higher initial crack growth rates while not affecting subsequent propagation at long crack lengths (Fig 12). Thus the overall life of the component was shortened due to increased crack propagation rates at short crack lengths.

3.1.4 Residual Effects of Crack Tip Plasticity

Due to the extremely high stress concentration at the crack tip a plastic zone is developed. It has long been recognised that the initiation of fatigue damage is a plastic deformation process. The effects of the development of plastic deformation are seen in two ways, firstly as an area of plastically strained material at the crack tip, secondly as a wake of stretched material left behind by the advancing crack. The effect of the plastic zone at the crack tip is generally thought to increase the effective load cycle[4]. The wake of stretched material along the cracked surfaces will however close under tensile loading, reducing the effective load cycle[7].

That it is necessary to include both of these effects in crack propagation prediction has been recognised[47,48]. For short cracks the existence of a plastic wake behind the crack only becomes possible as the crack size increases. It is this effect which has been proposed by some investigators as the prime cause of higher growth rate of cracks than long cracks at the same ΔK level. This is supported by the observation of initially rapid crack growth from saw cuts as stated earlier. However the effects of the plastic zone itself cannot be ignored. The importance of the plastic zone in relation to crack growth rate has been measured by Inio[48] while Lankford[49] points to the correlation of the plastic zone size with fracture mode and growth rate after an overload. Similarly Mills[50] in studying load interaction effects concludes that the extent of the reduced growth rate due to overloading is related to the overload plastic zone dimension, clearly pointing to the need to ensure plastic zone sizes of small and large cracks are the same if crack growth grates are to be compared.

We conclude therefore that crack closure due to the deformed wake behind the crack tip can reduce the effective load cycle. At short crack lengths the wake will not have formed and the effective load cycle will therefore be greater than for a longer crack cycled at the same ΔK level. At high R ratios the crack has less potential to close and would be expected to show less short crack rapid growth than would a zero R ratio test. The plastic zone at the crack tip acts to increase the load cycle, by wedging the crack open. The size of the plastic zone is a function of ΔK. It is this aspect which is of concern in the technique of remachining specimens to reduce the length of cracks. Any residual plastic zone which remains could increase the effective load cycle on retesting, particularly so in ΔK_{TH} tests where the ΔK values will be considerably less than previously experienced by the specimen.

The Effects of Variable Amplitude Loading

Relatively few of the investigations which are available have been made under both constant amplitude and variable amplitude loadings where all other parameters have been maintained constant. Two which have are due to Fisher and Sherratt[16] and Edwards and Ryman[30]. Under bending conditions at zero mean load Fisher and Sherratt showed only small effects under both constant amplitude and random amplitude waveforms. Larger effects were seen under axial loading with a slight tendency for the random amplitude waveform to give more short crack enhancement, particularly at high stresses. The fretting work of Edwards and Ryman[37] broadly support this conclusion. Subsequently Cook et al[21] have measured crack growths at lengths down to 0.02 mm (0.001") in L65 notched specimens. Although accelerated crack growth at short crack length was not conclusively verified under constant amplitude loading it was very marked under variable amplitude loading (Fig 13). A prediction of the variable amplitude crack rates using linear summation from the constant amplitude data predicted crack rates that were too slow at short crack lengths and too fast at longer crack lengths.

3.2 Metallurgical Studies

3.2.1 Modes of Crack Origin

Cracks originate at points of high plastic strain and are formed by shearing action at 45° to the principle stress direction, in Mode 1. For practical materials the origin of damage does not necessarily control subsequent behaviour. Kanio[51] tested a steel with a 50/50 proportion of ferrite and martensite. He observed non propagating cracks in the ferrite were held below the ΔK_{TH} level in the martensite. Shimizu[52] noted that for high strength steels failures originated both from inclusions and changes in the matrix structure. Grimberg[53] in tests on Magnesium alloys observed differences in the growth mechanisms of surface microcracks and through cracks, since surface damage occurred with the formation of more brittle components.

Both Morris[54] and Stone and Swift[55] have observed crack origins at intermetallic particles below the surface. Typically these break through at fast growth rates at apparent (but false) short crack lengths.

3.2.2 Crack Growth Within the Microstructure

There is ample published work[22,53,55-65] to demonstrate a dependence of fatigue threshold and crack propagation rate on grain size. Numerous references are made in the literature to blocking of slip bands or pinning of cracks at the grain boundaries. It may be expected then, that the size of non propagating cracks would be related to grain size and that the short crack length might also be similarly related.

Tanaka[56] has suggested from his studies of intergranular crack growth that where cracks are stopped by slip bands blocked at grain boundaries, then the threshold stress intensity factor can be expressed as:

$$K_{TH} = \sigma_{TH} \sqrt{\pi a}$$

$$= K_c^m \sqrt{\frac{a}{b}} + 2\sqrt{\frac{a}{\pi}} \cdot \sigma_{fr} \cos^{-1} (a/b)$$

where K_c is the critical value of the microscopic stress intensity factor; σ_{fr} is the stress acting along the boundary of the blocked slip band; 2a is the intergranular crack length and 2b is the crack length plus the length of the blocked slip bands. From this the fatigue limit can be derived by putting $a = 0$.

$$\sigma = \sigma_{fr} + \frac{K_c^m}{\sqrt{\pi e}}$$

where e is the length of the slip band, this demonstrating an interrelationship between, threshold

K values, fatigue limit and grain size. Tanaka has used this approach to predict the behaviour of two steels with different grain size and has achieved good agreement. For the mean grain sizes examined (3.5 μm and 23.5 μm) it can be seen that an LEFM approach to ΔK_{TH} would be appropriate from crack sizes of less than 0.1 mm and 0.2 mm respectively (0.004" to 0.008").

A series of tests reported by Taira[61] covered fatigue testing in reverse bending ($R = -1$) and crack propagation tests ($R = -1$, 0 and 0.5). Among his findings were observation of earlier initiation in larger grain size material, the absence of any stage II crack growth at stresses under the fatigue limit and blockage of slip bands at grain boundaries. At stresses above the fatigue limit he found crack nucleation either along the slip band or at the grain boundaries, with subsequent propagation in stage II. He found evidence not only of slip band blocking but also of crack interaction which delayed propagation. However he did state that even when the crack length was the order of the grain size the growth rate followed the same law as established for large macrocracks until deceleration occurred due to crack interaction or grain boundary interaction. He replaced ΔK with ΔK_{eff} where ΔK_{eff} took account of the crack opening stress. He found that for $R = -1$ the crack opening stress varied within the load cycle dependent upon ΔK, being in the compression part of the cycle for high ΔK values and in tension at ΔK near to threshold. Using this approach (ie ΔK_{eff}) the Paris equation was used to fit the data down to growth rates of ¯ x 10^{8} mm/cycle for all grain sizes. He did find that ΔK_{TH} increased as $(\text{grain size})^{\frac{1}{2}}$ and that the slip band zone was related to $(\Delta K)^2$ except near the threshold. He suggested that a change from structure sensitive to structure insensitive behaviour occurred where the grain size and slip band zone were near the same.

Lankford[62] in studies of specimens loaded while under observation in the SEM has reported a spectrum of behaviour with cracks stopping at or near grain boundaries while others have propagated at a fast rate (Fig [illegible]). His observations have identified a stress dependence, with tests at high stress levels (like Pearson's[9]) showing no tendency to be retarded while others at low stress levels are arrested and can subsequently become non propagating. Within these bounds other tests have shown varying amounts of retardation to the fast rate.

Studies of the behaviour of crack tips adjacent to grain boundaries have been made by Morris[53,63,64] with important conclusions. He studied the effect of proximity of grain boundary on plastic zone size and crack tip opening. He found a non continuum nature of deformation for cracks of approximately the grain size in length. Crack tips with large crack opening displacement had large crack closure stresses, characteristically associated with the beginning of propagation into a large grain. As the crack tip approached a grain boundary the growth rate was fast because in this state the crack closure stress was small, while at some distance from a boundary the closure stresses were large and propagation rate was low. These observations were made at high stress levels (90% yield) and must be related to Lankford's observations. Together they show a mechanism for variability in crack growth rate which is grain size dependent.

In summary the effects of grain size on fatigue limit and crack growth threshold are as shown schematically on Fig 14. The recent work which has studied behaviour related to grain size dependence may be used to extend LEFM to smaller crack sizes.

4 RELEVANCE OF STRESS INTENSITY FACTOR SOLUTIONS

The correlation of crack growth rate and stress intensity factor, on which the use of LEFM in crack growth prediction depends, has been universally accepted. There is a danger in this acceptance that insufficient attention is paid to the accuracy of the determination of the K solution. It has already been pointed out that the effects which Talug observed correspond to an error in K evaluation of only 3% or so. Yet the crack shapes seen in the laboratory rarely correspond to the idealised shapes seen in standard K solutions. Sometimes only small changes in ΔK are necessary to align small crack and long crack data at the very steep part of the $^{da}/_{dn}$, ΔK curve near threshold. Most long crack data are obtained from through crack tests where crack fronts are relatively straight and such crack front bow as does exist is unimportant. Short cracks however are almost invariably three dimensional problems where stress intensity factor solutions are less well established and less amenable to adaptation to fit actual crack front shapes. It must also be remembered that since cracks originate in shear, stage I as defined by Forsyth[66], it is not sufficiently accurate to apply Mode I crack opening K solutions until the cracks become established as stage II cracks.

Several authors have assumed that surface flow lengths correspond to semi circular crack fronts. Many others, having examined fracture surfaces, remark upon change in crack shape[12,25,26,33,39,67], usually changing from semi circular to semi elliptical, but sometimes changing again in response to surface factors. The inherent changes in K should be, but are not always, taken into account. Remembering the small changes in K which are critical at the low value of ΔK this is a serious limitation. Even for a perfectly semi circular crack front there is not universal agreement on the correct computation of the stress intensity factor[68,69] (Fig 15). It is most probable that the range of solutions actually used would give rise to variations in the K values obtained of 10% or more.

The question of shape is even more complex for corner flaws. McGowan and Smith[71] have shown that the K values at the bore and the surface (for a crack at the corner of a hole) reverse in importance as the crack grows. Wiltshire and Knott[72] showed increased toughness of corner flaws compared to through cracks, a result which could arise from differences in accuracy of K computation for the two cases.

An additional complication arises from the location of the crack origin relative to the structural feature. Moon[40] found that for a loaded hole the crack originiated down the bore but near to the corner. Such a location would give rise to observations of crack growth rate on the free surface apparently at much shorter crack lengths than actual. Rice and Brock[2] however found that cracks always originated on the corners of holes and moreover were not attracted by particles; Rudd and Grey[73] linked crack initiation sites to anodized pits and Powell[27,28] found that cracks at holes originated at the corner or down the bore of the hole depending upon stress level.

Whereas K values for a through crack vary only a little along the crack front, the local K values along the curved crack front of a three dimensional solution show substantial variation[74]. It is not at all clear what value of K should be taken for correlation with crack growth rate, nor in general, what value individual investigators have assumed.

Short cracks by their nature are in plane stress conditions throughout the length of the crack front. Long cracks may or may not be, depending upon material thickness. Comparison of short and long crack behaviour based upon crack growth data for thick specimens of the same material, as might be done for long specimens for example, introduces more uncertainty to the validity of the comparison, since the relationship of plane stress to plane strain data and to mixed conditions is not well understood.

5 DETERMINATION OF THE SIZE LIMIT OF THE SHORT CRACK

From basic considerations Smith[75] has determined the short crack length limit from requirements on the relative size of plastic zone and near crack tip field relative to crack length. He argues from the standpoint that to limit errors in stress analysis the near crack tip field should be limited to $^1/_{10}$ of the crack length. Similarly the plastic zone size should be limited to $^1/_5$ of the near crack tip field. Both of these limitations are accepted as a necessary condition for toughness testing and together imply that the crack length must be at least 50 times larger than the smallest significant feature in the material at the crack tip. Smith suggests that this feature should be a typical subgrain slip band with a representative size of 0.5 μm. Thus the minimum crack size at which LEFM could be expected to apply would be 0.025 mm.

Near notches much larger plastic zones will be generated and the crack length at which LEFM could be used will be determined by the notch geometry and the applied stress. The short crack length as determined by Smith will be enclosed by the yielded material. In these circumstances Smith and Miller[76] have proposed that crack growth will be controlled not by short crack limitations but by the fatigue limit stress, and that cracks will grow under combined notch plasticity and crack tip growth under LEFM (Fig 16).

The experimental work reported and summarised earlier agrees to a very reasonable degree with Smith's calculations. There are definite indications that short crack limits for unnotched specimens and specimens with small surface pits are of the order 0.1 mm and show a grain size dependence which accords with Smith's approach. There are also very strong indications that notches can be treated in an analogous manner with the grain size as an initiation length, a further length up to (say) 10 times grain size in which elastic plastic fracture mechanics can be used to characterise crack growth, and a general applicability of LEFM from this length onwards (Fig 17). For many materials this means that LEFM and EPFM can be used from about the same crack size for plain material and notched material respectively.

6 SHORT CRACK GROWTH PREDICTION TECHNIQUES

Prediction techniques fall broadly into two classes:

a. those which set out to modify the LEFM approach, in order to increase applicability to smaller crack lengths or perhaps to define the crack length below which LEFM will not apply:

b. those which attempt to model the behaviour within the grain with a transition to LEFM as crack growth proceeds.

The development of these models is encouraging since there is promise in some respects of defining initiation time and hence, together with LEFM, a technique for calculation of time for whole life.

Dowling[77] and Le Fort[78] have both defined the short crack limitation at notches as the length in which the effect of the stress concentration dies away. Dowling suggests:-

$$e = \text{notch radius}\left[\left(\frac{\text{stress x stress concentration}}{\text{yield stress}}\right)^{\frac{1}{2}} - 1\right]$$

For materials with conventional yield to ultimate ratios e should not exceed 0.2 x notch radius, thus defining a maximum length to the short crack. Le Fort seeks to use the stress gradient as a local stress in calculations and also to define maximum length for the short crack effect. His maximum depth turns out to be:

$$e = \frac{1}{2}\,\text{notch radius}\left(\frac{\text{notch depth}}{\text{notch radius}}\right)^{\frac{1}{3}}$$

There is clear similarity between these two expressions.

Barnby and Holder[20] suggest that short crack anomalies are contained within the Neuber particle and that beyond this size LEFM applies. The total life is then obtained from the time to traverse the Neuber particle plus crack propagation life.

In a series of papers El Haddad[1[illegible],79,80] and co-authors have developed the approach of length enhancement to increase the calculated stress intensity factor and hence the crack growth rate as calculated. They have used the junction of the fatigue limit and the applicability of LEFM (Fig 9) as their value of length enhancement. That is:

$$da/dn = C\left(\Delta\sigma\sqrt{\pi(a + \ell_o)}\right)^n$$

$$\text{where} \quad \ell_o = \left(\frac{\Delta K_{TH}}{\text{smooth fatigue limit}}\right)^2 \frac{1}{\pi}$$

This approach has received some use in analysis of data, chiefly because of the ease with which it can be applied, but an acceptable physical justification has yet to be developed. It should be noted that a mean load dependence is obtained through the relationship of ΔK_{TH} to R ratio.

Edwards[57] in analysis of fretting fatigue also used an enhanced stress intensity factor. His enhancement was to the mean value of the stress intensity factor range, to reflect mean stress effects directly.

More recent work has been published by Kitagawa[57] who used a strain intensity factor to define crack growth down to the smallest size measured in his tests. He used:

$$K_\varepsilon = \varepsilon\sqrt{\pi a} = \eta\,(\Delta\sigma)^n\sqrt{\pi a}$$

$$da/dn = C\,\eta^m\,(\Delta\sigma)^{(n-1)m}\,(\Delta K)^m$$

Tanaka[] as previously described has developed a prediction for K_{TH} based upon slip band boundary stresses.

Morris[] observed crack growth which was retarded or stopped as the crack reached a grain boundary. He has proposed a new growth model which allows discontinuous growth behaviour. The model includes crack closure stress as a function of the distance of the crack tip to a grain boundary and a cessation of growth across a grain boundary pending the development of a mature plastic zone in an adjacent grain. The model is claimed to describe crack growth from 30 to 300 μm in an aluminium alloy with mean grain size 75 μm. Crack growth is obtained from:

$$da/dn = \left(C\;\Delta K_{eff}\right)^n$$

$$\text{where} \qquad \Delta K_{eff} \propto \left(\tau_{max} - \tau_{CL}\right)\sqrt{a}$$

$$\text{and} \qquad \frac{\tau_{CL}}{\sigma_{max}} = \frac{\emptyset\,[\text{Distance crack tip to grain boundary}]}{2a}$$

and the incubation period N_d is obtained from a material parameter β as:

$$\beta = \int_{N_S}^{N_S + N_d} D\sqrt{2a\;N}\left(\Delta\tau_{eff} - \Delta\tau_o\right)^2 dN$$

7 CONCLUSIONS

There is considerable variability in the comparison of crack growth rate at short and long crack lengths. While some investigations have failed to show short crack effects others have demonstrated substantial increases in crack propagation rate and also decreased crack growth threshold values of stress intensity factor. Short crack effects, when observed, often do not remain effective at crack lengths much above 0.1 mm. However some investigations have shown effects up to 0.2 mm with one isolated example of persistence up to 1 mm.

There are good reasons for questioning the validity of some of the data either on grounds of specimen preparation or test technique. Overall however the evidence of short crack effects is strong and on theoretical grounds it can be shown that for thresholds they should exist.

A number of techniques for prediction of short crack effects have been developed and cover determination of threshold values, definition of the short crack length from which LEFM applies, and calculations of crack growth rates. Even so there is no one technique as yet which is both simple and easy to use, readily determined without specialised testing, and which can also be justified on physical grounds. There are empirical corrections which can be applied and, in the circumstances tested so far, give useful results. Perhaps the most satisfying for immediate application is use of elastic plastic fracture mechanics, which has been shown to apply down to the grain size.

Particular problems arise from surface conditions. In general these can be reduced to accounting for the appropriate stress gradients in the stress intensity factor solutions. However in many instances these surface stresses are ill defined but of considerable magnitude. More work needs to be done to define these conditions before an appreciation of short crack effects in the presence of surface stresses, however caused, can be put on firm ground.

There are good prospects that from the increasing importance being given to short crack studies a new understanding of initiation will develop with consequent improvement in total life prediction techniques.

REFERENCES

1. Anon. *Airplane Damage Tolerance Requirements.* Military Specification MIL-A-83444 (USAF) 1974.

2. Rice, R.C. Broek, D. *Evaluation of Equivalent Initial Flaws for Damage Tolerance Analysis.* NADC-77250-30, September 1978.

3. Forman, R.G. *Study of Fatigue Crack Initiation from Flaws using Fracture Mechanics Theory.* Eng. Fracture Mech. 4, 2, 333 (1972).

4. Crooker, T.W. ASME Paper 71 PVP-2.

5. Elber, W. *The Significance of Fatigue Crack Closure.* In *Damage Tolerance in Aircraft Structures* ASTM STP 486.

6. Tracy, D.M. *Conference on Finite Element Techniques in Fracture Mechanics.* Stuttgart 1973.

7. Nicholl, R. Private Communication (1982).

8. De Lange, R.G. *Plastic-Replica Methods Applied to a Study of Fatigue Crack Propagation in Steel 35 CD 4 and 26 St Aluminium Alloy.* Trans. Met. Soc. of AIME. Vol. 230, 644 (1964).

9. Pearson, S. *Initiation of Fatigue Cracks in Commercial Aluminium Alloys and the Subsequent Propagation of Very Short Cracks.* Eng. Fracture Mech. 7, 2, 235 (1975).

10. Peel, C. Private Communication (1981).

11. Schijve, J. *Significance of Fatigue Crack in Micro Range and Macro Range.* In *Fatigue Crack Propagation.* ASTM STP 415.

12. Schijve, J. *Differences between the Growth of Small and Large Cracks and the Relation to Threshold K Values.* Delft University of Technology Report LR327.

13. Broek, D. *The Propagation of Fatigue Cracks Emanating from Holes.* N.L.R. TR 72134 U (1972). Int. Symposium on Fatigue Thresholds (June 1981). Aeronautical Research Institute of Sweden.

14. Morrow, S.M. RAE Report in preparation. *Residual Strength of Fatigue Cracked Stiffened Panels.*

15. Anstee, R.F.W. Unpublished data used in 'Concorde' certification.

16. Reifsnyder, K. Talug, A. *Analysis and Investigation of Small Flaws.* In *Cyclic Stress-Strain and Plastic Deformation Aspects of Fatigue Crack Growth.* ASTM STP 637.

17. Fisher, B.C. Sherratt, F. *A Fracture Mechanics Analysis of Fatigue Crack Growth Data for Short Cracks.* In *Fracture Mechanics in Engineering Practice.* Ed. P. Stanley. App. Science Pub.

18. El Haddad, M.H. et al. *J. Integral Applications for Short Cracks at Notches.* Int. Journal of Fracture. Vol. 16 p. 15 (1980).

19. Dowling, N.E. *Crack Growth During Low Cycle Fatigue of Smooth Axial Specimens.* In *Cyclic Stress-Strain and Plastic Deformation Aspects of Fatigue Crack Growth.* ASTM STP 637

20. Barnby, J.T. Holder, R. *Fatigue from Notches in Cast Steels.* Metal Science 11, 1, p. 5 (1977).

21. Cook, R. Edwards, P.R. Anstee, R.F.W. *Crack Propagation at Short Crack Length under Variable Amplitude Loading.* Proc. Eleventh ICAF Symposium, Noordwijkerhout. 1981.

22. Lankford, J. *Initiation and Early Growth of Fatigue Cracks in High Strength Steel.* Eng. Fracture Mech. 9, 3, p. 617 (1977).

23. Lankford, J.; Cook, T.S.; Sheldon, G.P. — *Fatigue Microcrack Growth in a Nickel-Base Superalloy*. Int. Journal of Fracture 17, 2, p. 143 (1981).

24. Lankford, J.; Cook, T.S.; Sheldon, G.P. — *Growth of Small Fatigue Cracks at High Temperature — Applicability of Conventional Fracture Mechanics*. ICF-5 Cannes, France, 1981.

25. Starkey, M.S.; Irving, P.E. — *The Influence of Microstructure on Fatigue Crack Initiation in Spheroidal Graphite Cast Irons*. International Conference on Low Cycle Fatigue, Stuttgart (1979).

26. Starkey, M.S.; Irving, P.E. — *Prediction of Fatigue Life of Smooth Specimens of S.G. Iron using a Fracture Mechanics Approach*. International Symposium on Low Cycle Fatigue and Life Prediction. Firming (1980).

27. Starkey, M.S. — *Contribution to the Euromech Colloquium on Short Cracks*. Sheffield University, 1982.

28. Powell, P.M. — *The Behaviour of Short Fatigue Cracks Growing from Holes in 7178 and 7075 Al. Alloy Plate*. University of Southampton Report ME 80 7 (1980).

29. Powell, P.M. — *Further Observations on Short Fatigue Cracks Growing from Holes in 7075 and 7010 Al. Alloy Plate*. University of Southampton Report ME 80 19 (1980).

30. Peel, C.J.; Forsyth, P.J. — *The Analysis of Fatigue Failures*. 12th ICAS, 80 0.3. Proceedings 12th ICAS. Munich 1980.

31. Peel, C.J. — *The Role of Fatigue Testing in the Assessment of the Airworthiness of Aircraft Structure*. Lecture at the Institute of Mechanical Engineers, London (1980).

32. Frost, N.E.; Pook, L.P.; Denton, K. — *A Fracture Mechanics Analysis of Fatigue Crack Growth Data for Various Materials*. NEL 22 1 69 (1969).

33. Kitagawa, H.; Takahashi, S. — *Applicability of Fracture Mechanics to Very Small Cracks or the Cracks in the Early Stage*. Proceedings of the 2nd Int. Conf. on Mech. Behaviour of Materials, August 1976.

34. Kitagawa, H.; et al. — *Quantitative Analysis of Fatigue Process — Microcracks and Slip Lines Under Cyclic Strains*. In *Fatigue Mechanisms* ASTM STP 675.

35. Murakami, Y.; Endo, T. — *Effects of Small Defects on Fatigue Strength of Metals*. International Journal of Fracture 16, 1, p. 23 1980.

36. Nisitani, H.; Takao, K. — *Successive Observations of Fatigue Process in Carbon Steel, 7-3 Brass and Al Alloy by Electron Microscope*. Trans JSME 40 No. 340 p. 3254 (1974).

37. Edwards, P.R.; Cook, R. — *Fracture Mechanics Predictions of Fretting Fatigue under Constant and Variable Amplitude Loading*. 11th ICAS, B 5 03. Proceedings of 11th ICAS, Lisbon 1978.

38. Leadbeater, G.; et al. — *Fractographic Investigation of Fretting-Wear and Fretting-Fatigue in Aluminium Alloys*. Fatigue of Engineering Materials and Structure, Vol. 3 p. 237 (1981).

39. Moon, J.E. — *Crack Growth in Pin Loaded Lugs*. Paper 2.9 in *Aircraft Fatigue in the Eighties*, the 11th ICAF Symposium, Noordwijkerhout, Netherlands, May 1981.

40. Heath-Smith, J.R.; Aplin, Judy E. — *The Effect of an Application of Heat on the Fatigue Performance under Random Loading of a Notched Specimen of DTD 5014 (RR58) Material*. RAE Technical Report 71209, 1971.

41. Forsyth, P.J.E. — *The Microstructural Changes that Drilling and Reaming can cause in the Bores of Holes in DTD 5014 (RR58 Extrusions) and the Effects of Subsequent Heating*. Aircraft Engineering, November 1972.

42. El-Helieby, S.O.A.; Rowe, G.W. — *Influences of Surface Roughness and Residual Stress on Fatigue Life of Ground Steel Components*. Metals Technology 7, 6, p. 221 (1980).

43. A.S.T.M. — *Fatigue Crack Growth under Spectrum Loads.* ASTM STP 595.

44. Chandawanich, N.; Sharpe, W.N. — *An Experimental Study of Fatigue Crack Initiation and Growth from Coldworked Holes* Eng. Fracture Mech. 11, p. 609 (1979).

45. Rich, D.L.; Impellizzeri, L.F. — *Fatigue Analysis of Cold Worked and Interference Fit Fastener Holes.* In *Cyclic Stress Strain and Plastic Deformation Aspects of Fatigue Crack Growth.* ASTM STP 637.

46. Clark, G.; Knott, J.F. — *Effects of Notches and Surface Hardening on the Early Growth of Fatigue Cracks.* Metal Science 11, 8/9, p. 345 (1977).

47. Frost, N.E.; Marsh, K.J.; Pook, L.P. — *Metal Fatigue.* Published by Clarendon Press, Oxford.

48. Lino, Y. — *Accumulated Plastic Zone around Fatigue Crack in Type 304 Stainless Steel.* Metal Science 10, 5, p. 159 (1976).

49. Lankford, J. et al. — *Fatigue Crack Tip Plasticity.* In *Cyclic Stress Strain and Plastic Deformation Aspects of Fatigue Crack Growth.* ASTM STP 637.

50. Mills, W.J. et al. — *Load Interaction Effects on Fatigue Crack Growth in A 514 F Steel Alloy.*

51. Kunio, T.; Yamada, K. — *Microstructural Aspects of the Threshold Condition for Nonpropagatory Fatigue Cracks in Martensitic Ferritic Structure.* In *Fatigue Mechanisms.* ASTM STP 675.

52. Shimizu, M. et al. — *Structural Changes during the Fatigue Process of High Hardened Steel.* Trans. JSME 36 No. 281 p. 17 (1970).

53. Grinberg, N.M.; Serdyuk, V.A. — *Parameters and Micromechanisms of Fatigue Crack Growth in Sheet Magnesium Alloy Samples.* Int. Journal of Fatigue. July 1981.

54. Morris, W.L. — *Metallurgic Transactions A.* 10A p. 5 1979.

55. Stone, M.; Swift, T. — *Future Damage Tolerance Approach to Airworthiness Certification.* Paper 2.9 in *Structural Fatigue as a Design Factor.* 10th ICAF Symposium, Brussels, Belgium, May 1979.

56. Tanaka, K.; Nakai, Y.; Yamashita, M. — *Fatigue Growth Threshold of Small Cracks.* Int. Journal of Fracture 17, 5, p. 519 (1981).

57. Kitagawa, H.; Takahashi, S. — *Transactions.* Japan Soc. Mech. Eng. 45, p. 1289 (1979).

58. Nakai, Y.; Tanaka, K. — *Grain Size Effect on Growth Threshold for Small Surface Cracks and Long Through Cracks under Cyclic Loading.* Proceedings 23rd Japan Congress on Materials Research, 1980.

59. Gerberich, W.W.; Moody, N.R. — *A Review of Fatigue Fracture Topology Effects on Threshold and Growth Mechanisms.* In *Fatigue Mechanisms.* ASTM STP 675.

60. R.O. Ritchie — *Near-Threshold Fatigue Crack Propagation in Steels.* International Metals Reviews. Nos. 5/6 1979.

61. Taira, S.; Tanaka, K.; Hoshina, M. — *Grain Size Effect on Crack Nucleation and Growth in Long-Life Fatigue of Low-Carbon Steel.* In *Fatigue Mechanisms.* ASTM STP 675.

62. Lankford, J. — *Contribution to the Euromech Colloquium on Short Cracks.* Sheffield University, 1982.

63. Morris, W.L. — *The Noncontinuum Crack Tip Deformation Behaviour of Surface Microcracks.* Metallurgical Transactions A. 11 A, p. 1117, 1980.

64. Morris, W.L.; James, M.R.; Buck, O. — *Growth Rate Models for Short Surface Cracks in Al 2219 — T851.* Metallurgic Transactions A. 12A, p. 57, 1981.

65. Miller, K.J. *Contribution to the Euromech Colloquium on Short Cracks.* Sheffield University, 1982.

66. Forsyth, P.J.E. *Two-Stage Process of Fatigue Crack Growth.* Proceedings of the Crack Propagation Symposium, Cranfield 1961.

67. Vosikovsky, O.; Rivard, A. *Growth of Surface Fatigue Cracks in a Steel Plate.* Int. Journal of Fatigue, p. 111, July 1981.

68. Newman, J.C. *A Review and Assessment of the Stress Intensity Factor for Surface Cracks.* In *Part Through Crack Fatigue Life Prediction.* ASTM STP 687.

69. Benchmark Editorial Committee, SESA *A Critical Evaluation of Numerical Solution to the Benchmark Surface Flaw Problem.* Experimental Mechanics, p. 253. August 1980.

70. Petrovic, J.J.; Mendiratta, M.D. *Fracture from Controlled Surface Flaws.* In *Fracture Mechanics Applied to Brittle Materials.* ASTM STP 678.

71. McGowan, J.J.; Smith, C.W. *Stress Intensity Factors for Deep Cracks Emanating from the Corner formed by a Hole Intersecting a Plate Surface.* In *Mechanics of Crack Growth* ASTM STP 590.

72. Wiltshire, B.; Knott, J.F. *The Toughness of High Strength Maraging Steels Containing Short Cracks.* Int. Journal of Fracture 16 (1980).

73. Rudd, J.L.; Gray, T.D. *Quantification of Fastener Hole Quality.* Journal of Aircraft 15, 3, p. 143 (March 1978).

74. Raju, I.S.; Newman, J.C. *Improved Stress Intensity Factors for Semi Elliptical Surface Cracks in Finite Thickness Plates.* NASA TMX 72825 (August 1977).

75. Smith, R.A. *On the Short Crack Limitations of Fracture Mechanics.* Int. Journal of Fracture, 13, p. 717 (1977).

76. Smith, R.A.; Miller, K.J. *Fatigue Cracks of Notches* Int. Journal of Mechanical Science 19, p. 11 (1977).

77. Dowling, N.E. *Notched Member Fatigue Life Predictions Combining Crack Initiation and Propagation.* Fatigue of Eng. Mat. and Struct. 2, 2, p. 129.

78. Lefort, P. *Stress Intensity Factor for a Circumferential Crack emanating from a Notch in a Round Tensile Bar.* Eng. Fracture Mechanics, 10, 4, p. 897 (1978).

79. El Haddad, M.H.; Topper, T.H.; Topper, T.N. *Methods for Predicting Material Life in Fatigue.* Proceedings, Winter Meeting, NY. ASME 1979.

80. El Haddad, M.H.; Smith, K.N.; Topper, T.H. *A Strain Based Intensity Factor Solution for Short Cracks Initiating from Notches.* In *Fracture Mechanics.* ASTM STP 677.

81. Lankford, J. *On the Small Crack Fracture Mechanics Problem.* Int. Journal of Fracture, 16, R7, 1980.

82. Elsender, A.; Hopkins, P.; Batte, A.D. *Fatigue Crack Growth Threshold Data for Low Alloy Steels.* Metals Technology 7, 6, p. 256 (1980).

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14. Abstract

The two papers included in this Report were presented at the 52nd Meeting of the Structures and Materials Panel as the first stage of a study of the problems encountered in predicting the behaviour of short cracks. The fracture mechanics approach is being used for fatigue life assessment and durability evaluation of aircraft structures. Conventional crack growth prediction methods applied to smaller crack length ranges have met limited success so far. Short cracks may grow somewhat faster than expected by predictions using fracture mechanics data obtained from long crack specimens. The behaviour of short cracks obviously is affected by some analysis and additional secondary loading effects not normally accounted for in the stress intensity determination but having likely effects in short crack growth.

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